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(57) Abstract

A mesh telecommunications network with improved reliability for transporting information, known as traffic, is presented. The network includes a plurality of nodes interconnected by a plurality of links. Nodes direct the flow of traffic into, out of, and through the network, and links provide the means of traffic transport between nodes. Each pair of connected nodes has a number of links therebetween. Most links provide dedicated traffic transport, while at least one link is a spare link that can be selectively used with other spare links to form alternative traffic paths for restoring traffic that has been disrupted by one or more inoperative working links. Spare links can be pre-connected to form selectable standby alternative traffic paths for substantially immediate alternative traffic transport. Preferably, control of the network is decentralized to enable nodes to more quickly form alternative traffic paths and to reduce the likelihood of network-wide failures.

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MESH NETWORK WITH HIGH RESTORATIVE CAPACITY

Background of the Invention

This invention relates to telecommunications networks. More particularly, this invention relates to apparatus and methods for improving the reliability of mesh telecommunications networks. Improved reliability is achieved by providing high restorative capacity for restoring network integrity should portions of the network become inoperative.

Networks are ubiquitous; they are the backbone of many services and conveniences. For example, automated teller machines are part of banking networks that conveniently increase access to banking services. Many modern retail cash registers are part of a network used by retailers to track sales, set prices, and maintain inventory. Telephone, computer, and cable TV systems are all further examples of services made possible by telecommunication networks.

Common to these networks is the transport of some kind of information, in one form or another, from a source to a destination. This information, which can represent, for example, computer data, voice transmissions, or video signals, is known as "traffic." Traffic enters a network usually at a node, is transported through the network via links and other nodes until a destination is reached, and then exits the network usually at another node. Nodes provide the

routing necessary to either input (or "add") new traffic to the network, output (or "drop") traffic from the network, or direct traffic from one portion of the network to another. Links provide traffic paths between nodes. Overseeing the operation of a network is some kind of control. Control may be centralized, where all traffic management decisions are made by a central controller, or decentralized, where individual nodes have limited traffic management capabilities.

Networks vary in size and complexity. For example, a network could consist of a handful of computers connected together in a single office, or could consist of millions of telephone customers connected together across a continent.

Network configurations also vary. For example, a "mesh" network is one in which most nodes are connected to three or more other nodes. A symmetrical mesh network, as shown in FIG. 1A, results when each node is connected to an equal number of other nodes (except at the periphery of the network). An asymmetrical mesh network, as shown in FIG. 1B, results when nodes are connected to a variable number of other nodes. A ring network, as shown in FIG. 1C, is an interconnection of "rings," in which nodes and links are connected in a circular fashion.

Links can be of various transmission media, but more commonly, are either fiber-optic cable or coaxial cable. Individual links can vary in length from a few feet to hundreds of miles. Links that are part of a larger network, such as a telephone system, are usually carried on overhead utility poles, in underground conduits, or in combinations of both.

Nodes can range in complexity from simple switching or relay devices, as may be found in smaller networks, to entire buildings containing thousands of devices and controls, as may be found in larger

networks. Nodes can be implemented electronically, mechanically, optically, or in any combination thereof.

Nodes, generally known as cross-connects, perform a variety of functions. They perform basic traffic routing such as adding traffic to, dropping traffic from, and directing traffic through the network. Nodes also provide status to a network control system. In those networks where control is centralized, nodes simply transmit status to, and execute instructions from, the control system. In those networks with decentralized control, nodes are more complex enabling them to communicate with other nodes and make traffic routing decisions. Thus, nodes serve a variety of purposes based on the type of network control and the particular needs of a given network location.

The amount of data transported by a network can be very large. Typical data transfer rates for a fiber-optic link can range from 2.5 gigabits per second to 10 gigabits per second. A "bit" is a binary digit, which is the basic unit of computer data. A "gigabit" is a billion bits. Accordingly, any disruption in network traffic flow can be devastating. Of particular concern are telephone networks, where hundreds of thousands of individual communications could be transporting through the network simultaneously. Thus, network reliability, that is, the continuous availability and operation of a network, is commonly a top priority of network operators.

Network control and link integrity are two areas that can have the greatest impact on network reliability. For example, a control system malfunction is likely to affect some, if not all, of a network's performance. Link failures cause tremendous traffic losses (2.5 to 10 gigabits per second). Thus, to improve network reliability, backup control systems

must be provided to maintain control should the main control system fail, and spare links should be installed to permit rerouting of traffic disrupted by link failures.

One known mesh network that includes such reliability features is a long distance telephone network. A central controller monitors and controls the entire network, and several back-up systems ensure continuous operation. Each node communicates with the controller, sending status and receiving instructions for properly routing traffic. Working links connect the nodes and provide dedicated pathways for transporting traffic. A number of spare links, which do not regularly transport traffic, are installed in particular areas to provide alternative pathways for rerouting traffic that has become disrupted by an inoperative working link.

A link can become inoperative in a number of ways, but most often, when it is cut. This usually occurs, for example, when excavation occurs over an underground link, or when a traffic accident or severe storm damages a utility pole carrying a link.

Although these incidents are rare, typically occurring only about once per year, when one does occur, the nodes connected to the inoperative link immediately notify the controller. The controller then determines whether either enough spare links, spare capacity on working links, or combinations of the two, are available to reroute the disrupted traffic. Once an alternative traffic path is determined, the controller then sends appropriate instructions to those nodes that can interconnect the identified spare links and working links to form the alternative traffic path. Typical recovery time from such a disruption is approximately two seconds. This recovery time was once hailed as a marvel of technology; today, however, it is

no longer acceptable. A two-second outage would adversely affect, for example, the transmission of computer data. In fact, an entire computer center could be adversely affected by such an outage.

Contributing to the unacceptable recovery time is the network's centralized control. Nodes in such a network do not usually have the capability of communicating directly with other nodes to restore traffic disruptions. Thus, nodes affected by a link disruption must first communicate the disruption to the central controller, await instructions, and then, along with selected adjacent nodes, execute the received instructions to form the alternative path. This process undesirably increases recovery time.

Further, because centralized control renders a network more susceptible to network-wide disruptions should a malfunction occur, complex and expensive network-wide backup systems are needed to protect against such possibilities. This undesirably increases the cost of equipment, personnel, and maintenance for this type of network.

Another known network that improves upon the mesh network described above is a ring network. Nodes are connected in a circular fashion to form rings, and multiple rings are interconnected to form the complete network. Nodes are either add/drop multiplexers (ADMs) or cross-connect switches. An ADM adds or drops traffic from the network or simply forwards traffic to the next node. A cross-connect switch interconnects one ring with another. Control in this network is decentralized, enabling nodes to make limited traffic routing decisions. Although the rings are interconnected, each ring operates independently of the others thus desirably reducing the possibility of a network-wide failure.

One ring of such a network is shown in

FIG. 2. Ring 200 includes nodes 202, 204, 206, 208, 210, and 212. The connections between each node are made with one working link and one spare link. If a working link becomes inoperative (e.g., is cut), the traffic transported by that link will be rerouted back around the ring through the spare links.

To illustrate, assume a break 214 occurs between nodes 202 and 204, as shown in FIG. 2, severing working link 215 and spare link 216. Nodes 202 and 204, sensing the disruption of traffic flow, communicate with adjacent nodes 212 and 206, respectively, which in turn communicate with adjacent nodes 210 and 208, respectively. These nodes then activate spare links 218, 220, 222, 224, and 226 to reroute traffic to nodes 202 and 204. Recovery time from such a disruption is typically in the microsecond to nanosecond range. A microsecond is a millionth of a second and a nanosecond is a billionth of a second. In that short amount of time, telephone customers would not realize that a link carrying their call was cut and rerouted, and transmitted computer data would likely suffer only the loss of a few bits of data, which would simply require retransmission of the lost bits. Thus, this network improves upon the performance of the previously described mesh network.

However, a disadvantage of this ring network is that restoration is limited to substantially only one inoperative working link per ring. If, for example, two working links were cut in the same ring, traffic flow could not be restored until at least one of the links was physically repaired. (One exception is the case where one of the two inoperative working links occurs between the nodes of an interconnecting ring, as shown in FIG. 3. Traffic can be restored by including spare link 324 of ring 322 with spare links 306, 308, 310, 312, 314, and 316 of ring 302 to

restore traffic disrupted by breaks 301 and 303. However, such an occurrence would be completely fortuitous and does not significantly diminish the severity of this disadvantage.) This disadvantage is not shared by the previously described mesh network, because most nodes in a mesh network are connected to three or more other nodes, increasing the likelihood that enough spare links or spare capacity would be available to completely restore traffic flow that was disrupted by multiple inoperative working links.

A further disadvantage of this ring network is the high percentage of links that are set aside as spare -- a full 50%. Thus, half the links in the network will either sit idle, or, at best, be underutilized with nonessential or low priority activity until needed to restore disrupted traffic flow. This high percentage of underutilized link capacity is undesirable in today's environment of ever increasing demand for computing and communications power and flexibility, which accordingly increases demands on network resources and reliability.

Consequently, a mesh network, with its greater number of nodal interconnections, appears to provide a better framework from which to improve network reliability without unduly burdening the network with a high percentage of underutilized resources.

In view of the foregoing, it would be desirable to provide a mesh telecommunications network with high restorative capacity for restoring network traffic flow should one or more working links become inoperative.

It would also be desirable to provide a mesh telecommunications network with a sufficient number of spare links for restoring disrupted traffic flow while reducing underutilized network resources.

It would further be desirable to provide a mesh telecommunications network with decentralized control to improve restoration time and to reduce the likelihood of network-wide failures.

Summary of the Invention

In accordance with this invention, there is provided a mesh telecommunications network with improved reliability for transporting traffic from a source to a destination. The network has high restorative capacity and includes nodes for adding, dropping, and directing traffic, and links for transporting traffic between nodes. Each connected pair of nodes has at least three links between them; at least two, known as working links, provide dedicated traffic transport, and at least one, known as a spare link, provides selectable alternative traffic transport should a working link become inoperative.

The network advantageously has decentralized control for reducing the likelihood of network-wide failures and for improving restoration time. Decentralized control improves restoration time by enabling nodes affected by inoperative working links to communicate directly with adjacent nodes to quickly establish alternative paths comprised of spare links. The allocation of spare links throughout the network is generally sufficient to provide complete restoration of typically disrupted traffic flow, while also reducing the typical amount of underutilized link capacity.

Brief Description of the Drawings

The above and other objects and advantages of the invention will be apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts

throughout, and in which:

FIGS. 1A, 1B, and 1C are each a representational diagram of a network configuration;

FIG. 2 is a representational diagram of a portion of a prior art ring network;

FIG. 3 is a representational diagram of a larger portion of a prior art ring network;

FIG. 4 is a representational diagram of a link connecting two nodes;

FIG. 5 is a representational diagram of a portion of a first embodiment of the present invention;

FIGS. 6A and 6B are representational diagrams of a portion of a preferred embodiment of the present invention;

FIG. 7 is a representational diagram of a portion of a third embodiment of the present invention; and

FIG. 8 is a representational diagram of a portion of a fourth embodiment of the present invention.

Detailed Description of the Invention

The present invention provides a mesh telecommunications network with improved reliability. The network transports information, known as "traffic," in one form or another, from a source to a destination. Traffic can represent, for example, computer data, voice transmissions, or video signals. The network includes a plurality of nodes and links. Nodes route traffic into the network, out of the network, and from one portion of the network to another. Such nodes are generally known as cross-connects. Links interconnect the nodes to provide a system of traffic paths, each link being connected to two nodes. A "mesh" network is configured such that most nodes are connected via links to three or more other nodes. Examples of mesh

networks are shown in FIGS. 1A and 1B.

Traffic enters the network usually at a node, is transported via a plurality of links and other nodes to a destination, and then exits the network usually at another node. "Traffic," as used herein, refers both to a single communication being transported through the network from a source to a destination, and to all communications being transported through the network from a plurality of sources to a plurality of destinations.

Links are advantageously fiber-optic cable for transport of traffic in optical signal form. Other transmission media, such as, for example, coaxial cable for electronic signal transport, could also be used. Each link provides two separate paths for transporting traffic between two nodes. As shown representationally in FIG. 4, link 401 has a first path 402 for transporting traffic from a first node 404 to a second node 406, and a second path 408 for transporting traffic from second node 406 to first node 404. For simplicity, each link is shown in the drawings as a double-headed arrow.

Links are allocated as working links and spare links. Most links are working links that provide dedicated traffic transport between the two nodes connected thereto. Spare links, which do not normally transport traffic, provide selectable alternative traffic transport for restoring traffic flow between nodes that have had one or more working links between them become inoperative. Thus, spare links, while enhancing network reliability, also constitute an underutilized network resource. Therefore, providing a sufficient number of spare links such that the network is adequately protected and yet not unduly burdened is one of the more advantageous features of the invention.

Nodes are complex structures containing thousands of devices and controls for routing and preferably managing traffic flow. The design of such nodes, and the components used within, are well known in the art. Nodes are implemented preferably electronically, but can also be implemented, for example, optically, mechanically, or in any combination thereof. Besides performing basic traffic routing functions, nodes are also in communication with a network controller via links, providing status and other control information.

Network control is advantageously decentralized, enabling nodes to communicate with adjacent nodes and make limited traffic routing decisions. This reduces the time needed to restore traffic flow disrupted by inoperative working links, because the nodes affected by the disruption can cooperate directly with adjacent nodes to establish alternative traffic paths, rather than having to first communicate the disruption to a controller, await instructions while the controller, which is likely handling other tasks as well, determines an alternative path, and then execute the received instructions.

Decentralized control also reduces the likelihood of network-wide failures. By distributing traffic management functions to nodes throughout the network, problems arising in a controller, such as hardware failures or software errors, are much less likely to affect the entire network.

Restoration of disrupted traffic flow is advantageously accomplished by connecting together a minimum number of spare links to form one or more alternative traffic paths to the nodes affected by inoperative working links. Generally, such inoperability occurs when a link has been cut or severed, such as when excavation cuts through an

underground conduit carrying a link, or when severe weather severs a link being carried on an overhead utility pole. An inoperative working link is sensed by the two nodes connected to that link. The two affected nodes then communicate the disruption to the network controller so repairs can be scheduled, and then cause the traffic from the inoperative links to be routed to spare links. Communication from the affected nodes to adjacent nodes is accomplished via spare links. The communication is detected by receivers in the spare links that cause the adjacent nodes to activate the appropriate switches to connect the spare links with other spare links to form the alternative traffic path. Programming within the nodes selects the most direct available alternative path.

Typical recovery times from such link disruptions are desirably in the microsecond to nanosecond range, dependent, in part, on the switching technology of the nodes.

A portion of a first embodiment of a network according to the present invention is shown in FIG. 5. Network 500 has a plurality of nodes that are advantageously electronic, and a plurality of links that are advantageously fiber-optic, connected in a symmetrical mesh configuration. Symmetry results from each node being connected to an equal number of other nodes (except at the periphery). Control of network 500 is advantageously decentralized. Each node can sense the operability of the links connected to it, and can communicate with adjacent nodes and the controller. Each connected pair of nodes has three links therebetween. Two of the links are working links and the other is a spare link. Thus, there is a spare link between every pair of connected nodes and only one-third of all links are spare links. This allocation of spare links is a 33.3% improvement in

underutilized link capacity as compared to the previously known ring network.

When network traffic is disrupted because of one or more inoperative links, traffic is restored as follows: assume a break 501 occurs between nodes 502 and 504, as illustrated in FIG. 5, severing working links 505 and 507 and spare link 506. Restoration of severed spare link 506 is unnecessary because it does not regularly transport traffic; thus there is no traffic flow to restore. To restore traffic flow from severed working links 505 and 507, nodes 502 and 504, acting in concert, first communicate the break via links to the controller (not shown) and then begin to substantially simultaneously form alternative traffic paths 510 and 520. Alternative traffic path 510 is made up of spare links 512, 515, and 517 and node switches 514 and 519. Alternative traffic path 520 is made up of spare links 522, 525, and 527 and node switches 524 and 529.

Alternative traffic path 510 is formed by node 502 communicating with node 513 via spare link 512 to activate switch 514. Switch 514 connects spare link 512 with spare link 515. Meanwhile, node 504 communicates with node 518 via spare link 517 to activate switch 519. Switch 519 connects spare link 517 with spare link 515, thus completing alternative traffic path 510.

Alternative traffic path 520 is formed similarly. Node 523, after receiving communication from node 502 via spare link 522, activates switch 524 to connect spare link 522 with spare link 525. Meanwhile, node 528, after receiving communication from node 504 via spare link 527, activates switch 529 to connect spare link 527 with spare link 525, thus completing alternative traffic path 520. Traffic flow previously provided by severed working links 505

and 507 is now restored to nodes 502 and 504.

The present invention is particularly effective in networks having greater numbers of links between nodes. For example, a portion of a preferred embodiment of a network according to the present invention is illustrated in FIGS. 6A and 6B. Network 600 is a symmetrical mesh network with decentralized control of traffic flow. In this network, each connected pair of nodes has four links connected therebetween, three working links and one spare link. Accordingly, every pair of connected nodes has a spare link connected therebetween, and only one-fourth of all links are spare links. This allocation of spare links represents a 50% improvement in underutilized link capacity as compared to the previously described ring network.

To facilitate explanation and understanding of the restoration process according to the principles of the present invention, each spare link in FIGS. 6A and 6B is shown as two separate unidirectional paths, each represented by a single-headed arrow, which indicates the direction of traffic flow.

In this preferred embodiment, spare links are preferably pre-connected in a standby mode as shown in FIG. 6A. For example, spare link 602a is connected by switches 623 and 603 to spare links 642b and 612a, respectively. Spare links 642b and 612a are then connected to spare link 632b via switches 643 and 633, respectively, to form a selectable unidirectional standby alternative path between nodes 610, 630, 640, and 620. Such selectable standby alternative paths are formed between each group of nodes. These standby paths significantly improve restoration time by providing established alternative traffic paths for substantially immediate transport of disrupted traffic flow. Furthermore, these standby paths can be modified

as needed by reconnecting the node switches to other spare links to form other alternative paths.

To illustrate the restoration of disrupted traffic flow in network 600, assume a break 601 occurs between nodes 610 and 620, disrupting traffic flow in working links 611, 613, and 615, as shown in FIG. 6B. To restore traffic flow, six unidirectional alternative traffic paths must be formed, three transporting traffic from node 610 to node 620, and three transporting traffic from node 620 to node 610.

Two of the six alternative paths are substantially immediately available via standby alternative paths; one standby path includes spare links 612a, 632b, and 642b, and the second standby path includes spare links 622b, 662a, and 652a. Thus traffic transported by one of the disrupted working links 611, 613, or 615 is substantially immediately restored by the two unidirectional standby paths. Programming within the nodes determines what traffic from the severed working links is transported by the standby paths.

A third alternative traffic path is preferably formed as follows: node 640, after receiving communication from node 620 via spare link 642a, activates switch 645 to connect spare link 642a with spare link 632a. Substantially simultaneously, node 630, after receiving communication from node 610 via spare link 612a, activates switch 635 to connect spare link 632a with spare link 612b, thus completing a third alternative traffic path between nodes 620 and 610.

Similarly and substantially simultaneously as the third alternative path, a fourth alternative traffic path is preferably formed as follows: node 650, after receiving communication from node 610 via spare link 652b, activates switch 655 to connect spare

link 652b with spare link 662b. Meanwhile, node 660, after receiving communication from node 620 via spare link 622b, activates switch 665 to connect spare link 662b with spare link 622a, thus completing a fourth alternative traffic path between node 610 and 620.

A fifth alternative traffic path is formed also substantially simultaneously as the third and fourth alternative paths preferably as follows: node 630, after receiving communication from node 610 via spare link 612a, activates switch 637 to connect the standby alternative path formed by spare links 614a, 672a, and 634b with the standby alternative path formed by spare links 682a, 684b, and 686b. Meanwhile, node 640, after receiving communication from node 620 via spare link 642a, activates switch 647 to connect the standby alternative path formed by spare links 682a, 684b, and 686b with the standby alternative path formed by spare links 644b, 692b, and 624a, thus completing a fifth alternative traffic path.

A sixth alternative path is formed substantially simultaneously as the other alternative paths preferably as follows: node 660, after receiving communication from node 620 via spare link 622b, activates switch 667 to connect the standby alternative path formed by spare links 624b, 694b, and 664a with the standby alternative path formed by spare links 666b, 696a, and 654a. Meanwhile, node 650, after receiving communication from node 610 via spare link 652b, activates switch 657 to connect the standby alternative path formed by spare links 666b, 696a, and 654a with the standby alternative path formed by spare links 656a, 674a, and 614b, thus completing a sixth alternative traffic path.

Complete traffic flow, previously transported by severed working links 611, 613, and 615, is now

restored to nodes 610 and 620. Restoration time is significantly improved over the prior art mesh network because of decentralized network control, sufficient numbers of spare links, pre-connected standby alternative paths, the accordingly limited number of neighboring nodes that needed to be communicated with -- in this case only four, nodes 630, 640, 650, and 660, and the limited amount of switching those neighboring nodes needed to perform to complete the alternative paths.

Furthermore, if any of the spare links that were used to form the alternative paths above had been unavailable (except the spare links connected directly to nodes 610 and 620, which must be available for complete restoration), it is likely that other spare links could have been used to form the alternative paths. The use of other spare links would likely result in longer alternative paths and longer restoration times because of the additional nodes to be communicated with and switches to be set, but alternative paths nonetheless. This improved restorative capacity clearly demonstrates one of the advantages of a mesh network over a ring network, where restoration is limited to typically one alternative path per ring.

The present invention is also effective in asymmetrical mesh networks, which have nodes that are not each connected to an equal number of other nodes. FIG. 7 illustrates a portion of a third embodiment of a mesh network according to the present invention. Network 700 is an asymmetrical network with decentralized control and a plurality of nodes, preferably implemented electronically, interconnected with a plurality of links, which are advantageously fiber-optic cable. Each connected pair of nodes has three links therebetween, two working links and one

spare link. Spare links are again shown as bi-directional paths represented by double-headed arrows. Note that the feature of pre-connected standby alternative paths could also be included here, and that the same principles of the invention would apply if there were four links between each connected pair of nodes, three working links and one spare link.

Referring to FIG. 7, restoration of traffic flow is as follows: assume a break 701 severs the links between nodes 710 and 720. Alternative traffic paths 731 and 753 can be formed substantially simultaneously to restore the traffic flow of working links 711 and 713 in the same manner as previously described for the embodiments shown in FIGS. 5 and 6B. Alternative path 731 is formed by connecting spare link 732 to spare link 734 via switch 736 at node 730. Spare link 734 is connected to spare link 742 via switch 744 at node 740, thus completing alternative path 731. Similarly, alternative traffic path 753 is formed by connecting spare link 752 to spare link 756 via switch 754 at node 750. Spare link 756 is connected to spare link 766 via switch 762 at node 760. Spare link 766 is connected to spare link 774 via switch 772 at node 770. Spare link 774 is connected to spare link 784 via switch 782 at node 780, thus completing alternative path 731.

As can be seen, even from the limited portion of network 700 shown, variations of alternative paths 731 and 753 are possible by connecting other spare links through other nodes. If, for example, spare link 766 had not been available, alternative path 753 could have been routed through node 740 with spare links 764 and 746. Moreover, depending on the interconnection of nodes not shown in FIG. 7, other alternative paths for restoring traffic flow could have been possible. Generally, the more nodal

interconnections there are, the more likely it is that several alternative paths are available, increasing the likelihood of complete restoration should multiple link failures occur.

FIG. 8 illustrates a portion of a fourth embodiment of a mesh network according to the present invention. Network 800 includes a plurality of electronically implemented nodes 802 interconnected by a plurality of fiber-optic links 804. However, instead of each link 804 transporting traffic sequentially, as in the previous embodiments, each link 804 transports a plurality of traffic in parallel. Parallel traffic transport is accomplished by transporting each plurality of traffic through the link at a unique transporting parameter. This parameter is preferably wavelength and the manner in which transport is accomplished is wavelength-division-multiplexing (WDM), which is known in the art.

Typically, up to eight wavelengths per link are possible, four wavelengths for each direction (i.e., four for transport from a first node to a second node, and four for transport from the second node to the first node). Note that while the number of wavelengths per link may likely increase with advancements in the state of the art, the principles of the present invention would still apply.

Each pair of connected nodes is connected by a single link, which is capable of transporting traffic at approximately 20 gigabits per second. Wavelength multiplexers 806, located at each node, provide the necessary wavelength modulated traffic multiplexing and demultiplexing, and translation from optical signal form to electronic signal form and vice versa.

Restorative capacity is established by setting aside at least one wavelength per direction as a spare. Thus, traffic can be transported at three

wavelengths per direction per link. Accordingly, the percentage of "spares" can be as low as 25% of the total number of wavelengths available for transporting traffic, the same percentage of spare links as in the preferred embodiment of the present invention. Spare wavelengths are then available for use in selectable alternative traffic paths. Nodes still provide the connections between links for transporting disrupted traffic, and the wavelength multiplexers provide the proper routing of wavelength modulated traffic into and out of the nodes. Furthermore, standby alternative paths can also be provided by appropriately presetting the multiplexers and node switches to accommodate traffic flow at a spare wavelength. Such paths would enable disrupted traffic flow to be substantially immediately rerouted. Forming additional or modified alternative traffic paths is then accomplished in the same manner as previously described for the embodiments shown in FIGS. 5, 6B and 7.

In each of the above embodiments, it is possible that several inoperative links may limit a network's ability to completely restore disrupted traffic flow. For example, referring to FIG. 6B, if a second break were to occur between nodes 610 and 630, complete restoration of traffic flow to and from node 610 could not be made. In these rare situations (recall that only one such break typically occurs per year in the known mesh network described previously), those traffic paths with a pre-determined higher priority will be restored. Network areas deemed critical or more vulnerable can be supplemented with either more nodal connections or more spare links to enhance the likelihood of a complete recovery under such atypical circumstances. Note that while additional spare links between connected pairs of nodes will increase restorative capacity, such additional

links will undesirably increase underutilized link capacity.

To partially offset underutilized link capacity, spare links can also be used to reduce traffic density. For example, if a particular working link or group of working links becomes saturated, that is, traffic is being transported at the maximum rate and more traffic awaits to be transported, spare links, if available, could be used to transport the additional traffic. Such situations could occur in peak demand situations, such as, for example, in a telephone network on Mother's Day when there is typically a significant increase in the number of calls. This flexibility improves network performance and further reduces underutilized link capacity.

Although the embodiments described above advantageously have decentralized control, the reliability improvements provided by the allocation of spare links or spare wavelengths are still applicable even in those mesh networks with centralized control. The restorative process will differ only in the time needed to form alternative traffic paths. The process of appropriate nodes activating appropriate switches to connect spare links will be identical, thus giving the centrally controlled network the same high restorative capacity as decentralized networks.

Thus it is seen that a mesh network with improved reliability is provided. One skilled in the art will appreciate that the present invention can be practiced by other than the described embodiments, which are presented for purposes of illustration and not of limitation, and the present invention is limited only by the claims which follow.

WHAT IS CLAIMED IS:

1. A mesh telecommunications network for transporting traffic from a source to a destination, said network comprising:

a plurality of nodes for directing traffic; and

a plurality of links interconnecting said plurality of nodes for providing traffic paths therebetween, wherein:

each connected pair of said plurality of nodes has at least three of said plurality of links therebetween, some links being working links for providing dedicated traffic transport and the remaining links being spare links for providing selectable alternative traffic transport, the number of said working links being greater than the number of said spare links.

2. The network of claim 1 wherein the number of said spare links connected between each connected pair of said plurality of nodes is one.

3. The network of claim 1 wherein said spare links are pre-connected to form selectable standby alternative paths.

4. The network of claim 1 wherein spare links comprise approximately one-third of said plurality of links.

5. The network of claim 1 wherein spare links comprise approximately one-fourth of said plurality of links.

6. The network of claim 1 wherein each one of said plurality of nodes can sense an inoperative

working link connected thereto.

7. The network of claim 1 wherein each one of said plurality of nodes can communicate with selected adjacent nodes.

8. The network of claim 1 wherein at least one of said plurality of nodes communicates with selected adjacent nodes when said at least one of said plurality of nodes senses an inoperative working link connected thereto.

9. The network of claim 1 wherein at least one of said plurality of nodes and selected adjacent nodes cause selected spare links to form alternative traffic paths for transporting traffic transported by at least one working link connected to said at least one of said plurality of nodes when said at least one working link becomes inoperative.

10. The network of claim 1 further comprising a central controller for monitoring traffic flow and directing restoration of disrupted traffic flow, wherein each one of said plurality of nodes communicates with said central controller.

11. The network of claim 10 wherein said central controller causes selected spare links to form alternative traffic paths for transporting traffic transported by at least one working link when said at least one working link becomes inoperative.

12. The network of claim 1 wherein said network is a symmetrical mesh network.

13. The network of claim 1 wherein said

network is an asymmetrical mesh network.

14. A mesh telecommunications network for transporting traffic from a source to a destination, said network comprising:

a plurality of nodes for directing traffic; and

a plurality of links interconnecting said plurality of nodes for providing traffic paths therebetween, each one of said plurality of links having the capacity to transport a plurality of traffic in parallel, each one of said plurality of traffic being transported in parallel having a different transporting parameter, wherein:

said each one of said plurality of links has a spare transporting parameter associated therewith for providing selectable alternative traffic transport for one of a plurality of traffic when one of said plurality of links transporting said one of a plurality of traffic becomes inoperative.

15. The network of claim 14 wherein said transporting parameter is wavelength.

16. The network of claim 14 further comprising pre-connected selectable standby alternative traffic paths associated with said spare transporting parameter for providing substantially immediate alternative traffic transport.

17. The network of claim 14 wherein each said spare transporting parameter comprises approximately one-third of the transporting parameters associated with said each one of said plurality of links.

18. The network of claim 14 wherein each connected pair of said plurality of nodes has at least one link therebetween.

19. The network of claim 14 wherein each one of said plurality of nodes can sense an inoperative link connected thereto.

20. The network of claim 14 wherein each one of said plurality of nodes can communicate with selected adjacent nodes.

21. The network of claim 14 wherein at least one of said plurality of nodes communicates with selected adjacent nodes when said at least one of said plurality of nodes senses an inoperative link connected thereto.

22. The network of claim 14 wherein at least one of said plurality of nodes and selected adjacent nodes cause traffic transported by a link connected to said at least one of said plurality of nodes to be routed with spare transporting parameters to selected links when said link becomes inoperative.

23. The network of claim 14 further comprising a central controller for monitoring traffic flow and directing restoration of disrupted traffic flow, wherein each one of said plurality of nodes communicates with said central controller.

24. The network of claim 23 wherein said central controller causes each one of a plurality of traffic to be routed with said spare transporting parameter through selected links for restoring traffic flow when a link transporting said plurality of traffic

becomes inoperative.

25. The network of claim 14 wherein each of said plurality of nodes is implemented electronically, said network further comprising a plurality of wavelength multiplexers for multiplexing and demultiplexing traffic and for translating traffic from optical signal form to electronic signal form and vice versa.

26. A method of restoring disrupted traffic flow in a mesh telecommunications network, said network comprising a plurality of nodes for directing traffic and a plurality of links interconnecting said plurality of nodes, wherein each connected pair of said plurality of nodes has at least three of said plurality of links connected therebetween, some of said at least three links being spare links, said method comprising the steps of:

sensing when traffic flow is disrupted;

selecting spare links to form alternative traffic paths; and

connecting said selected spare links to restore disrupted traffic flow.

27. The method of claim 26 further comprising the step of pre-connecting said spare links to form selectable standby alternative paths.

28. The method of claim 26 wherein one of said at least three links is a spare link.

29. The method of claim 26 wherein said step of sensing comprises the steps of:

sensing disrupted traffic flow by at least one node affected by said disrupted traffic flow; and

communicating said disrupted traffic flow from said at least one affected node to selected adjacent nodes.

30. The method of claim 29 wherein said step of selecting comprises the step of:

determining a sufficient number and location of said spare links by both said at least one affected node and selected adjacent nodes for efficiently restoring said disrupted traffic flow.

31. The method of claim 26 wherein said step of sensing comprises the steps of:

sensing disrupted traffic flow by at least one node affected by said disrupted traffic; and

communicating said disrupted traffic flow from said at least one affected node to a central controller.

32. The method of claim 31 wherein said step of selecting comprises the step of:

determining a sufficient number and location of said spare links by said central controller for efficiently restoring said disrupted traffic flow.

FIG. 1A

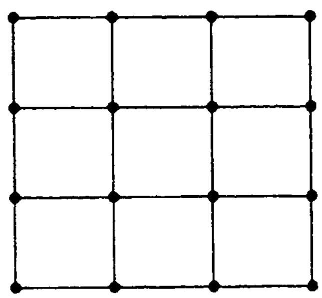

FIG. 1B

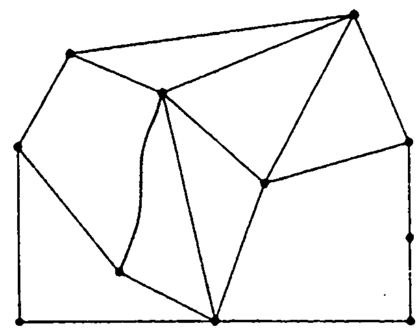

FIG. 1C

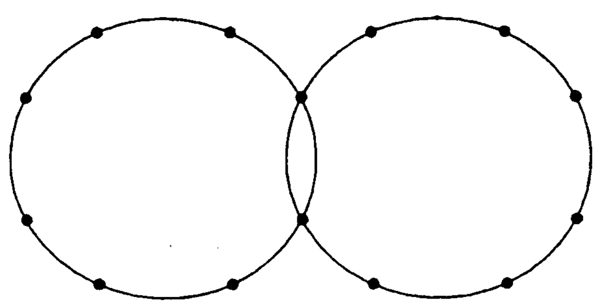

FIG. 2
(PRIOR ART)

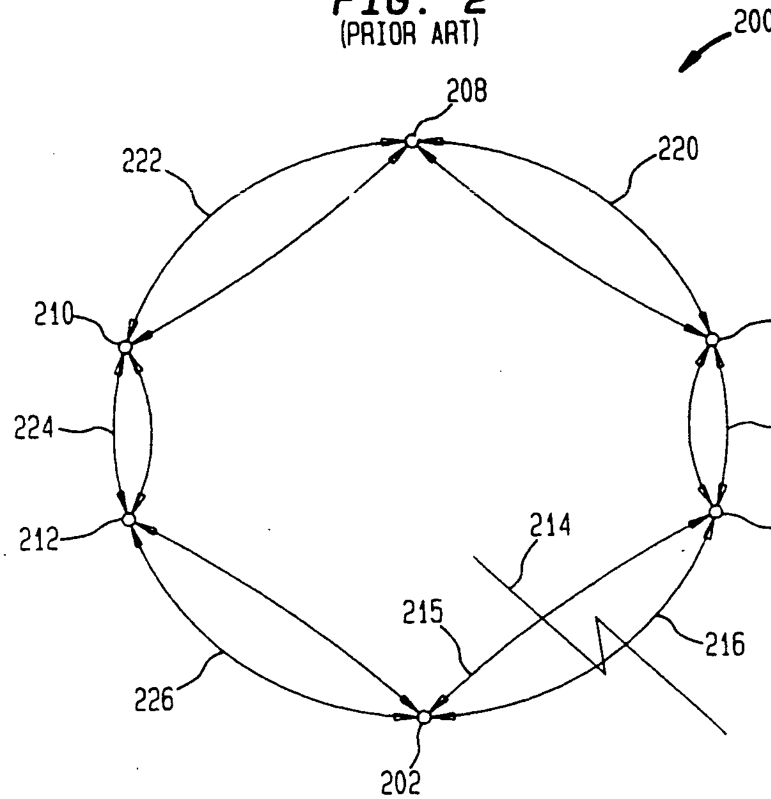

FIG. 3
(PRIOR ART)

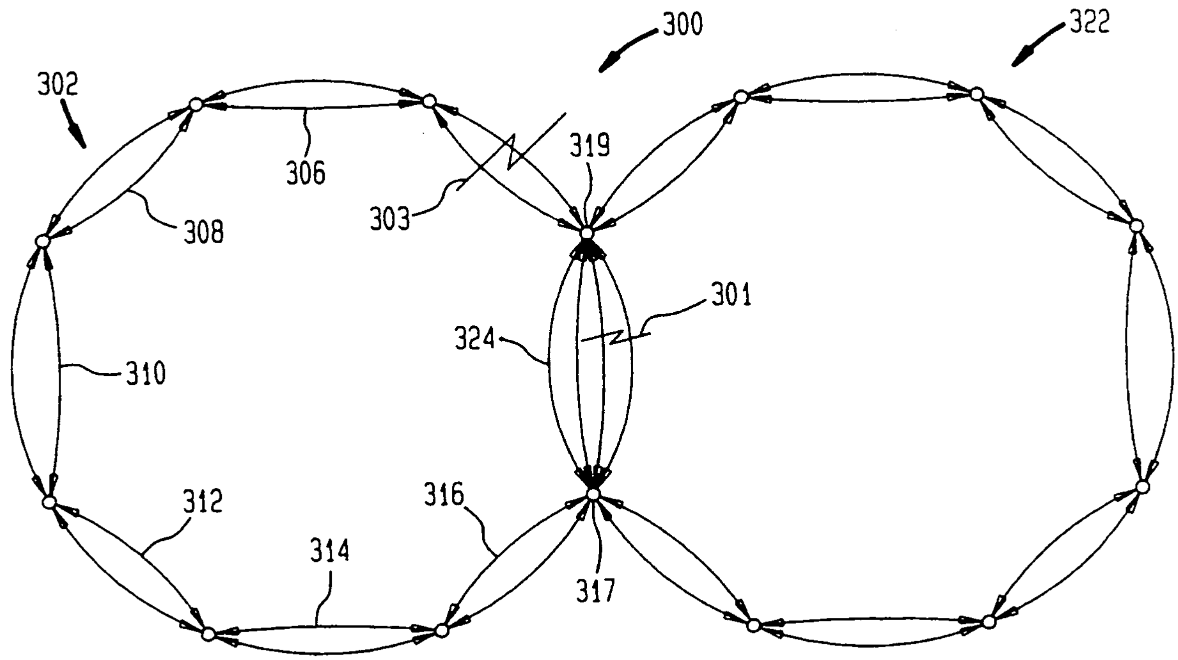

FIG. 4

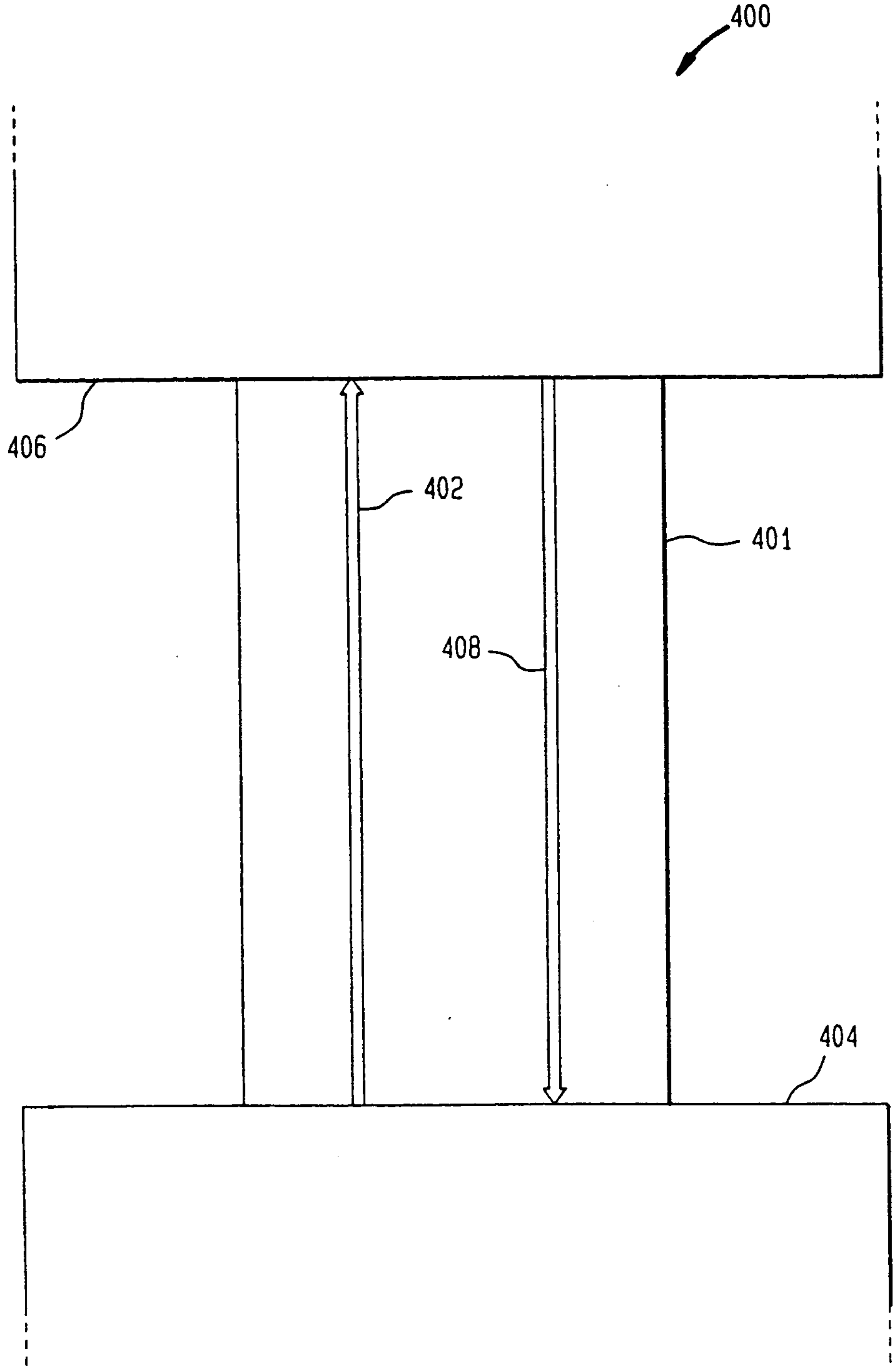

FIG. 5

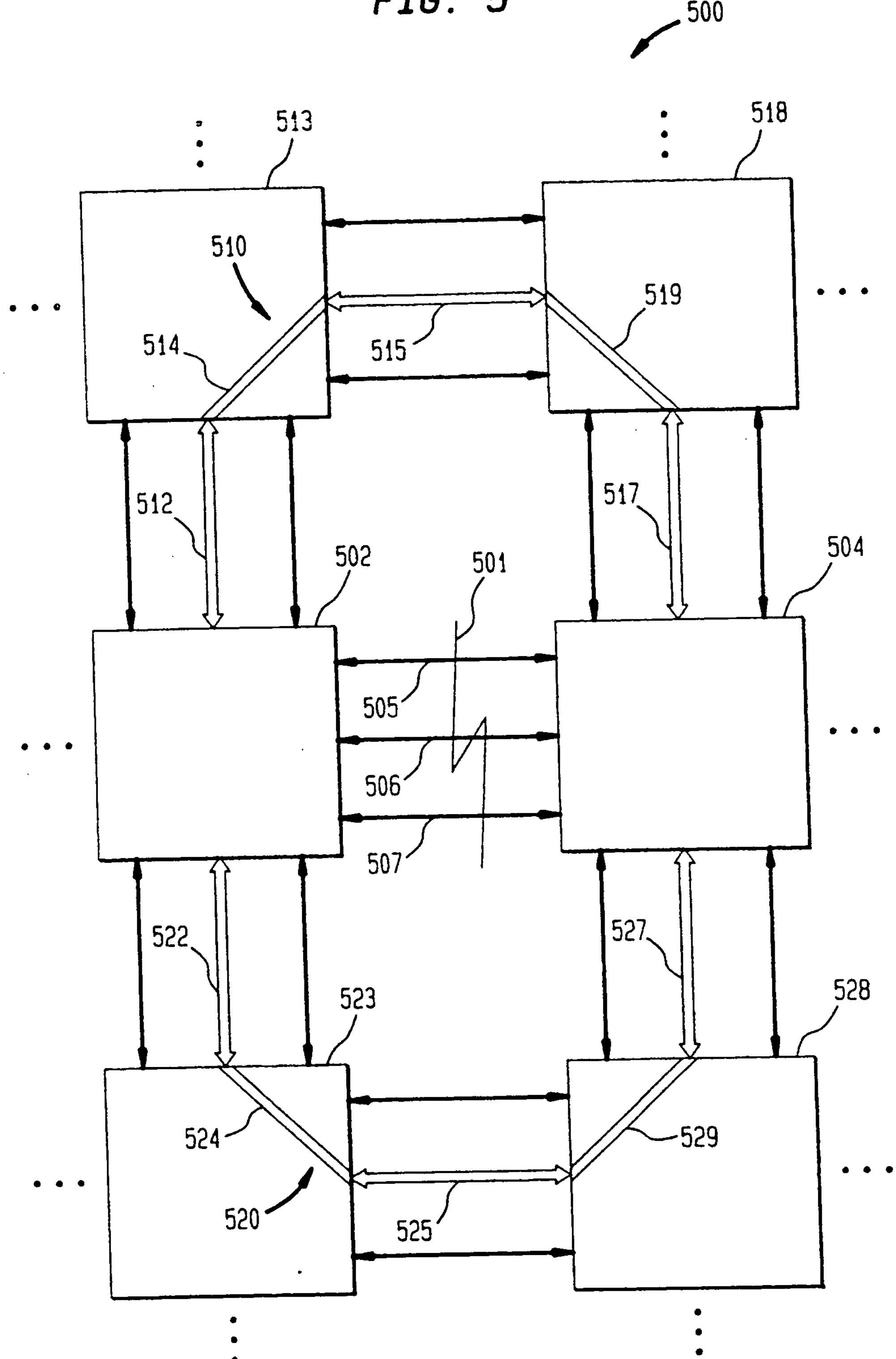
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FIG. 6A

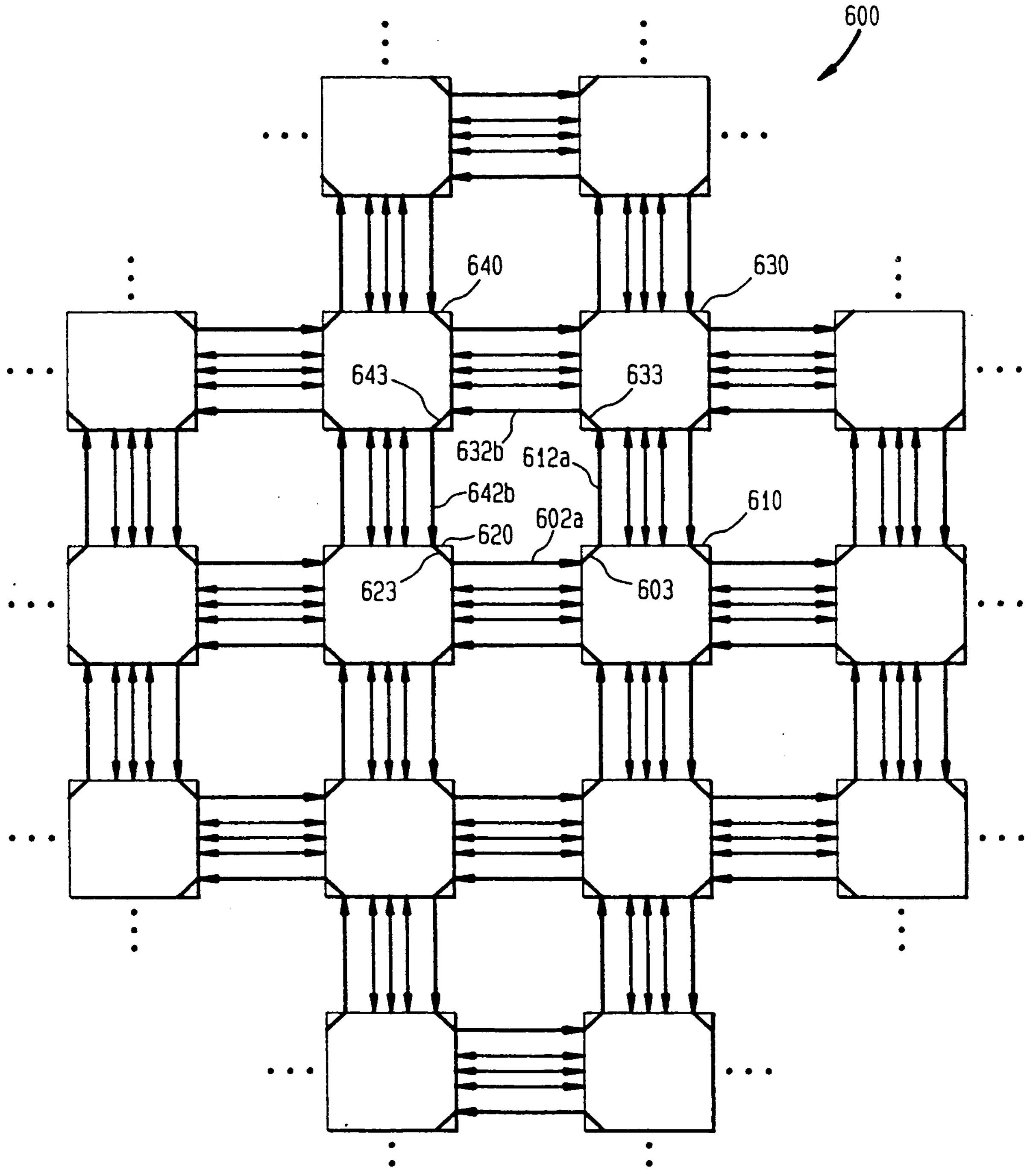

FIG. 6B

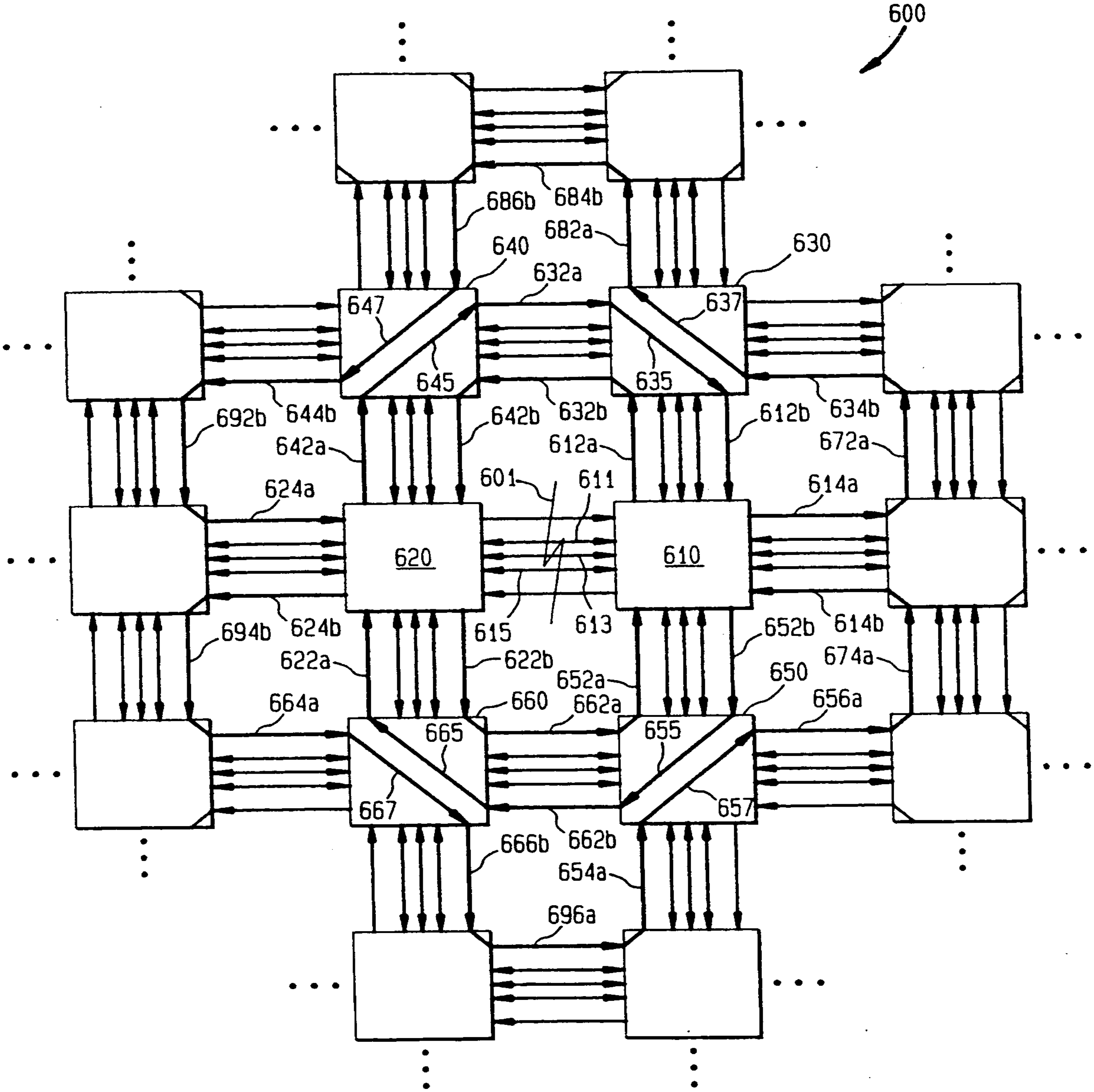

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FIG. 7

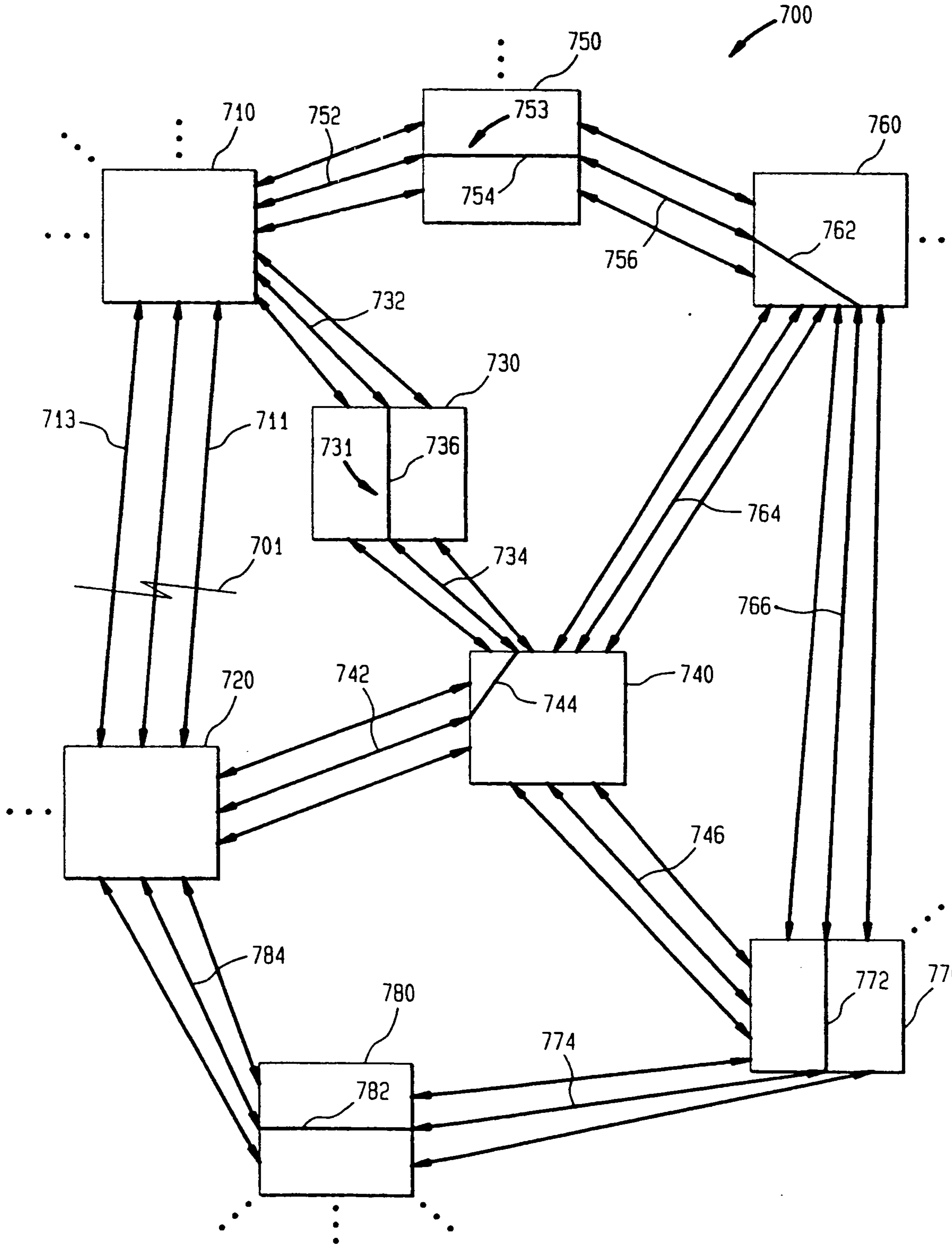
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FIG. 8